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# Thermal Optimized Operation of the Single-Phase Full-Bridge PV Inverter under Low Voltage Ride-Through Mode

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## Abstract

The efficiency of 98% has been reported on transformer-less photovoltaic (PV) inverters and the penetration of grid-connected PV systems is booming as well. In the future, the PV systems are expected to contribute to the grid stability by means of low voltage ride-through operation and grid support. At the same time, the target of a long service time (25 years or more) imposes new challenges to grid-connected transformer-less PV systems. Achieving more reliable PV inverters is of intense interest in recent research. As one of the most critical stresses that induce failures, the thermal stresses on the power devices of a single-phase full-bridge PV inverter are analyzed in different operational modes in this paper. The low voltage grid condition is specially taken into account in this paper. The analysis is demonstrated by a 3 kW single-phase full-bridge grid-connected PV system by simulations. The mean junction temperature and the junction temperature fluctuation of the power devices can be reduced by properly injecting reactive current into the grid under grid faults, and consequently, the overall lifetime of the entire PV system is improved.

## 1. Introduction

It is reported that the global installed photovoltaic (PV) capacity hit a new record by the beginning of 2013, being over 100 GW [1]. The development of single-phase PV systems connected to the public grid has been booming progressively in recent years as well, mainly due to the attractive feed-in tariff policies and the declined price of PV panels [2]-[4]. However, this interconnection also introduces negative impacts on the public network, which makes the grid much more uncontrollable and heterogeneous. Such concerns like power quality, efficiency and the emerging reliability are becoming of high interest [5]-[7]. Associated with appropriate control methods, the single-stage transformer-less inverters are adopted especially in European countries in order to obtain higher efficiency. The future electricity grid will be more interconnected with the renewables and more flexible [2]. It is consequently expected that the future PV system will have ancillary functions (e.g., low voltage ride through (LVRT) under grid faults) and it will have to be more reliable and more “smart” [5]-[11].

Normally, the reliability of a PV system can be increased by means of proper component selection (considering rated power and advanced packaging technologies) and effective thermal management. For a certain device or inverter, the only way to improve the reliability is to optimize its operation and enhance its control possibilities. As the essential interface components for PV panels and the grid, the single-phase inverters are one of the lifetime limiting and the most vulnerable parts in the entire PV systems as discussed in [12]-[17]. Many efforts are put into making the future PV system better in terms of reliability in order to ensure a high availability of the electrical power. In that case, the knowledge of the mission profiles of a certain application is firstly crucial for the reliability-based evaluation/design of power electronics in PV inverters as well as the operation of PV systems [13]-[17]. Various factors, like temperature, humidity and electrical overstress, induce the failures of PV inverters. Consequently, the PV system is likely required to endure both extremely ambient temperature changes and daily solar irradiance variations.

Besides these factors under normal operations in the consideration of the above mission profiles, the operation modes will also affect the lifetime of the whole system. Failures may be more prone to occur under non-intentional operations in islanding mode or in low voltage ride-through operation with reactive current injection, since the current loading on the power devices are changing with the operation modes. With thermal optimized operation in low voltage ride through operation mode, the reliability of the PV system will likely be improved.

As the reliability of the power switching devices is highly influenced by the temperature, it is of very importance to investigate the thermal loading, especially the junction temperature, of the switches applied in PV inverters. In this paper, firstly taking a constant operation ambient condition ( $1000 \text{ W/m}^2$ ,  $50^\circ\text{C}$ ) into account, the junction temperature cycling, which is one of the most critical stressors that causes failures, is addressed in different operation modes for a 3 kW single-phase full-bridge transformer-less PV system. Then, the system is tested under various solar irradiance levels (different power levels).

## 2. Thermal Models of PV Inverter

Fig. 1 shows the overall control structure of a single-phase full-bridge PV system, which is connected to the grid through an  $LCL$ -filter. In this system, if the voltage sag is detected, the operation mode will be switched to low voltage ride-through operation with reactive power injection. The thermal stresses on the power electronic devices, which are highlighted in Fig. 1, are investigated in this paper on the basis of the models shown in Fig. 2, since they have a significant impact on the reliability of the inverter. In Fig. 2, the impedance  $Z_{th(j-c)}$  is the thermal impedance from junction to case,  $Z_{th(c-h)}$  is the thermal impedance from case to heat sink and  $Z_{th(h-a)}$  is the thermal impedance from heat sink to ambient.

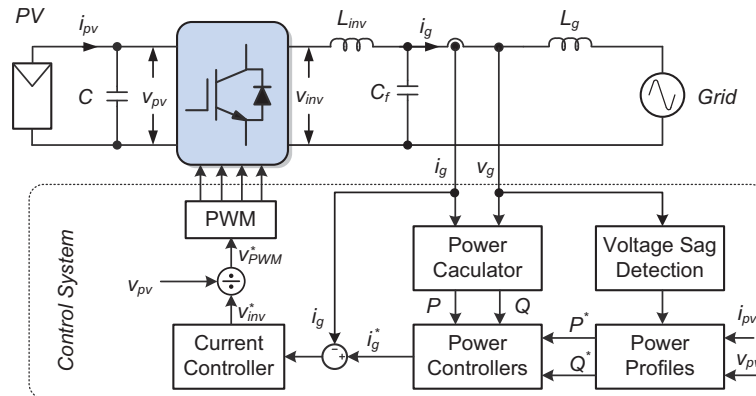


Fig. 1. Control structure of a single-phase full-bridge PV system based on single-phase  $PQ$  theory with low voltage ride-through capability [10], [11].

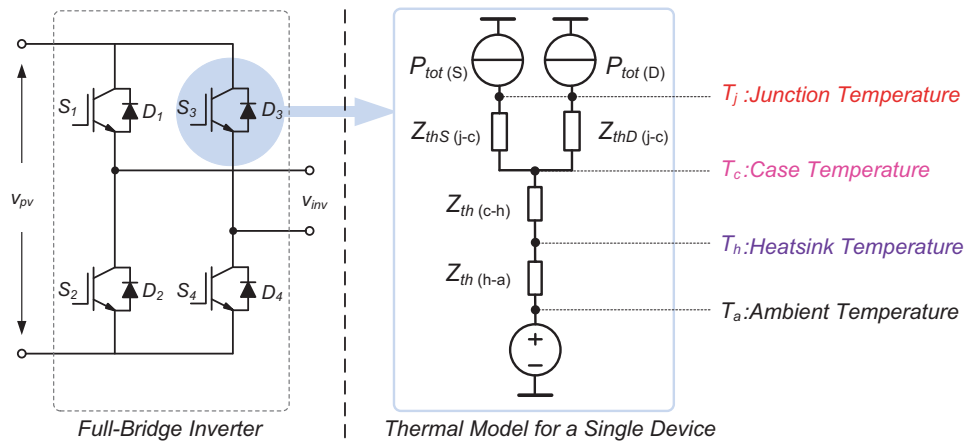


Fig. 2. Thermal model of an IGBT with a freewheeling diode in a power module [18], [20].

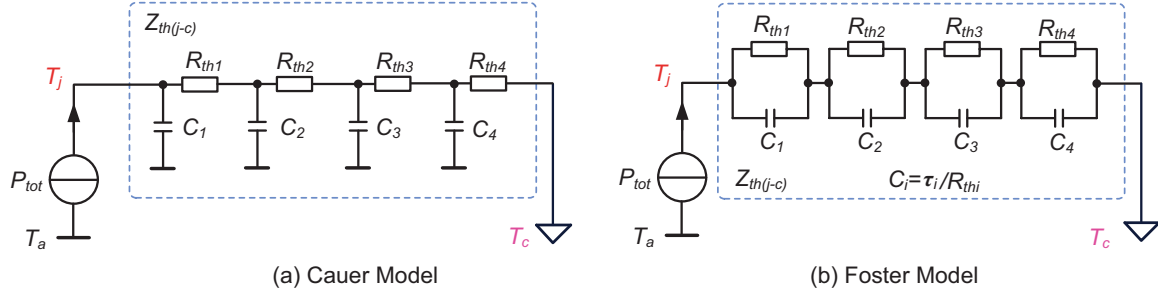


Fig. 3. Thermal models of the impedance  $Z_{thS(j-c)}$  or  $Z_{thD(j-c)}$  shown in Fig. 2 [20], [21].

In this study, a power module from a leading manufacture is selected. The thermal impedance  $Z_{thT(j-c)}$  or  $Z_{thD(j-c)}$  in Fig. 2 can typically be modeled as a Cauer RC network, as it is shown in Fig. 3(a). The Cauer Model is based on the physical behavior of a power device. Thus, the Cauer Model is a realistic representation and it is more accurate to reflect the thermal behavior of power switching devices. However, it is difficult to have the appropriate knowledge of the material properties of a selected device in order to build up such a model. The Cauer Model can be converted to a Foster Model, of which the thermal parameters are typically found in the datasheets. The Foster Model is a series-connected thermal impedances  $Z_{th}$  model as shown in Fig. 3(b), and compared to the Cauer Model, it is more suitable if a constant case temperature is assumed [20], [21]. According to Fig. 3, the analytical function of the thermal impedance can be described as [21],

$$Z_{th(j-c)}(t) = \sum_i^n R_{thi} (1 - e^{-t/\tau_i}). \quad (1)$$

It is also pointed out in [21] that the thermal models for the heat-sink including the interface material ( $Z_{th(c-h)}$  and  $Z_{th(h-a)}$ ) are necessary for the whole thermal model of a power module. Normally, those impedances are much larger than the thermal impedance from junction to case  $Z_{th(j-c)}$ . Thus, according to Fig. 2, the junction temperature for the IGBT or the free-wheeling diode can be expressed as,

$$\begin{aligned} T_{j(S/D)}(t) &= P_{tot(S/D)}(t) Z_{th(S/D)(j-c)}(t) + T_c(t) \\ &= P_{tot(S/D)}(t) Z_{th(S/D)(j-c)}(t) + [P_{totS}(t) + P_{totD}(t)] \cdot [Z_{th(c-h)}(t) + Z_{th(h-a)}(t)] \end{aligned} \quad (2)$$

in which  $T_{j(S/D)}$  and  $P_{tot(S/D)}$  are the junction temperature and the total power losses of the IGBT or the free-wheeling diode, respectively.

According to (1) and (2), it can be concluded that the steady-state mean value ( $t \rightarrow \infty$ ) of the junction temperature depends on the thermal resistance  $R_{thi}$ ; while the dynamic behavior of the junction temperature is dependent on the thermal capacitance  $C_i$  (with time constant  $\tau_i = C_i R_{thi}$ ). Moreover, the case temperature ( $T_c$ ) has a much slower dynamic response than that of junction temperature ( $T_j$ ) due to the large thermal impedances ( $Z_{th(c-h)}$  and  $Z_{th(h-a)}$ ) [21]-[23]. Therefore, for sake of simplicity, the case temperature is assumed to be constant as it has negligible impact on the dynamic thermal behavior of the junction temperature of the switching devices. The thermal parameters of the selected power module are listed in Table I. The maximum ambient temperature is set to be constant (50 °C) during the operation of the PV system in this study.

As it is indicated in (2) and Fig. 2, the junction temperature of a single IGBT module is also relevant to the total losses of the IGBT ( $P_{tot(S)}$ ) and the freewheeling diode ( $P_{tot(D)}$ ). This demonstrates that, by reducing the switching frequency, the total power losses of the device will decrease, leading to a lower junction temperature but a higher current total-harmonic-distortion. One possibility to reduce junction temperature in the normal operation is to de-rate

the output power of PV panels [19]. By this mean, the junction temperature will be kept below the maximum operational junction temperature. However, under grid voltage sags, the current may exceed the rated value, resulting in a very high junction temperature, if no specified control methods are adopted. Other possible solutions are using optimized modulation methods for a full-bridge inverter system or adopting modified transformer-less topologies where the current stress under low voltage ride-through might be reduced. However, it should be borne in mind that, to avoid leakage currents, the bipolar modulation is favorable for a single-phase full-bridge inverter connected to the grid without isolation transformer [22].

Table I. Foster thermal parameters for an IGBT module from a leading manufacture.

Impedance		$Z_{th(j-c)}$				$Z_{th(c-h)}$
$i$		1	2	3	4	
IGBT	$R_{thi}$ (K/W)	0.074	0.173	0.526	0.527	0.7
	$\tau_i$ (s)	0.0005	0.005	0.05	0.2	0
Diode	$R_{thi}$ (K/W)	0.123	0.264	0.594	0.468	0.7
	$\tau_i$ (s)	0.0005	0.005	0.05	0.2	0

Table II. Simulation parameters for a single-phase grid-connected PV system.

Nominal Grid Voltage	$V_{GRMS} = 230$ V
Nominal Grid Frequency	$f = 50$ Hz
Rated Power	$P_{pv} = 3$ kW
Nominal DC Voltage (PV Output Voltage, $V_{MPP}$ )	$V_{dc} = 400$ V
Switching Frequency	$f_{sw} = 10$ kHz
LC Filter	$L_{inv} = 3.6$ mH, $C_f = 2.35$ $\mu$ F
Grid Impedance	$L_g = 4$ mH, $R_g = 0.02$ $\Omega$

### 3. Thermal Optimized Operation

Referring to Fig. 1, a 3 kW single-phase PV system is developed in PLECS and it is simulated in different operation modes. The simulation parameters for the whole system are shown in Table II. The Proportional Integrator (PI) controllers are used to regulate the active power and the reactive power. A Proportional Resonant (PR) controller with Harmonic Compensators (HC) is adopted as the current controller to ensure the quality of the injected current. The bipolar modulation scheme is applied in this system in order to avoid the generation of leakage currents.

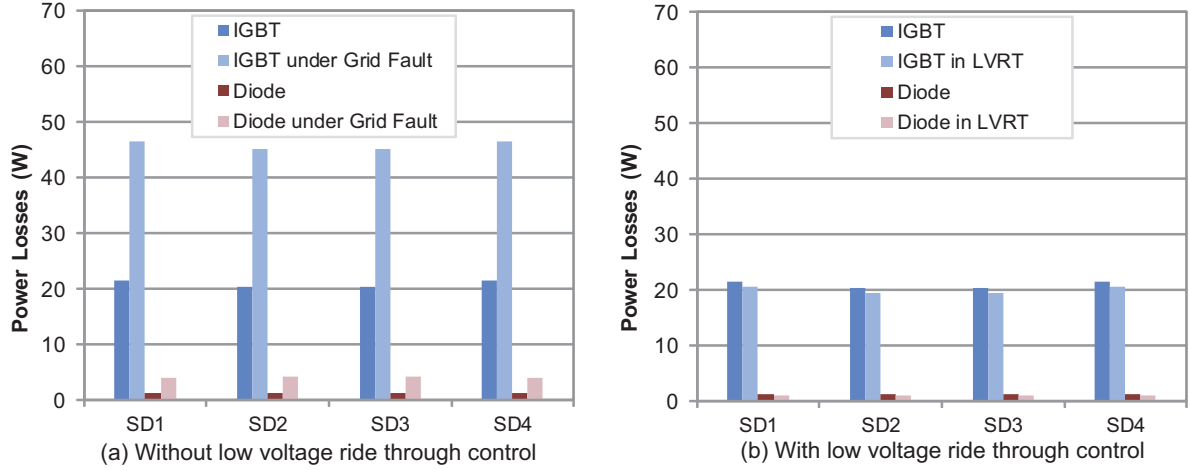
#### 3.1 System Low Voltage Ride-Through Operation

The system is firstly tested under grid faults. Once the voltage fault is detected by the sag detection unit shown in Fig. 1, the operation mode will be switched to low voltage ride-through operation mode from the normal operation condition with Maximum Power Point Tracking (MPPT). During LVRT operation, the system injects reactive power to the grid and limits active power at the same time to prevent the inverter from overcurrent protection.

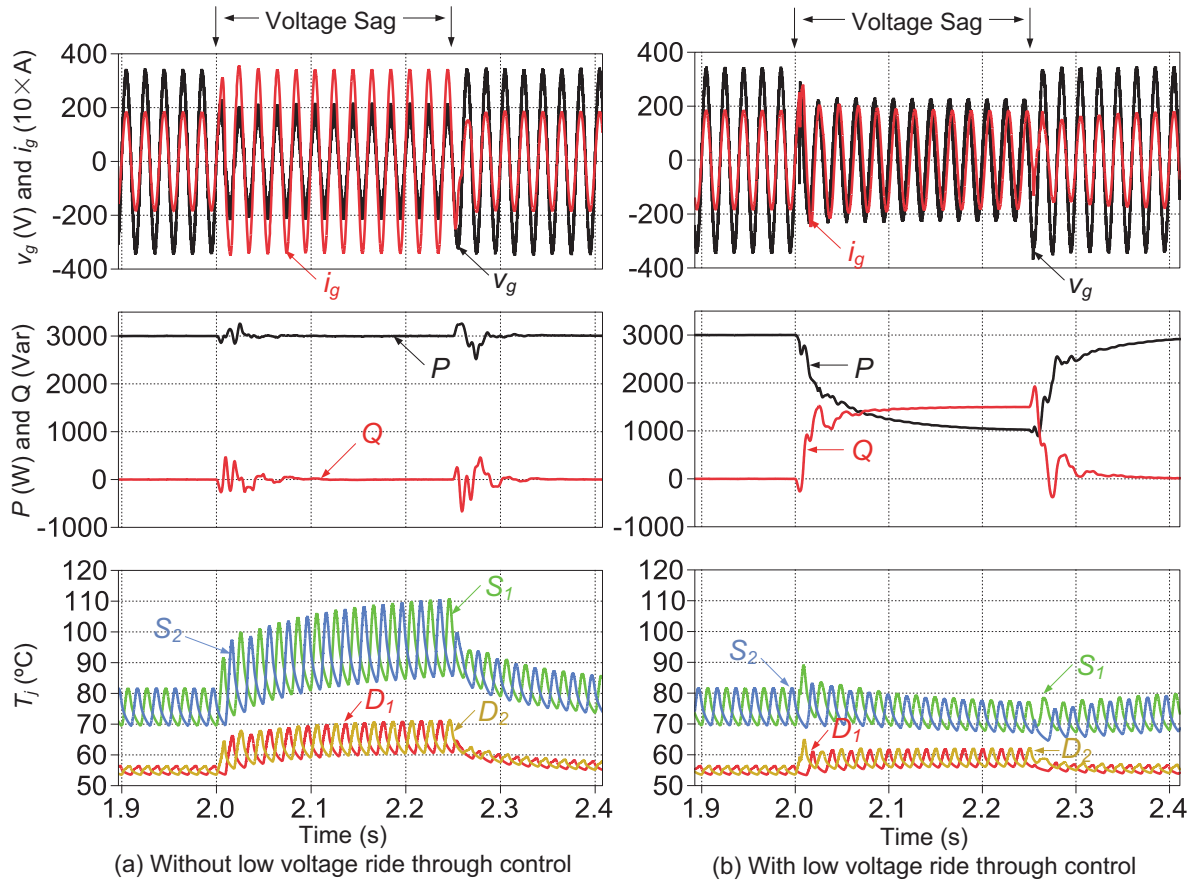
As it is discussed in the last paragraph in § 2, if no appropriate control methods are taken into action immediately after the voltage sag, the injected current amplitude is going to exceed the inverter rated current level, resulting in the inverter shutdown because of overcurrent protection. This is also a big challenge for the system reliability. Normally, the grid-connected PV system is required to cease energizing the local loads in such a case. However, with low voltage ride-through operation, it is not necessary for the PV system to disconnect from the grid, but it can inject reactive current in such a way to reduce the current loading on the devices and to improve the overall inverter reliability.

The simulation results are shown in Fig. 4 and Fig. 5. The power losses distribution is also presented in different operation modes since it decides the junction temperature of the power devices as it is shown in (2). Because the bipolar modulation scheme is adopted in this application, which means power switches  $SD1$  and  $SD4$  ( $SD2$  and  $SD3$ ) act at the same time, the power losses on the devices are similar as it is indicated in Fig. 4(a). It is also seen from Fig. 4 that by applying the thermal optimized operation (LVRT control) the power losses on the devices are significantly reduced, which results in a lower mean junction temperature. As it is also indicated in Fig. 5(a), when the grid is subjected to a 0.45 p.u. voltage sag, the

mean junction temperature increases if no LVRT control methods are adopted. In contrast, in the thermal optimized operation mode (with low voltage ride-through control) (Fig. 5(b)), by injecting reactive currents into the grid as required by the grid codes, the maximum junction temperature is reduced below the allowable one (i.e. the value from the datasheet). Moreover, the junction temperature fluctuation during LVRT is reduced to 10 °C (Fig. 5(b)) from 24 °C (Fig. 5(a)) by means of thermal optimized operation. In this way, the overall inverter reliability is improved.



**Fig. 4.** Power loss distribution of the single-phase full-bridge PV inverter in different operational modes (SD: IGBT Module; S: IGBT; D: Diode, referring to Fig. 2).



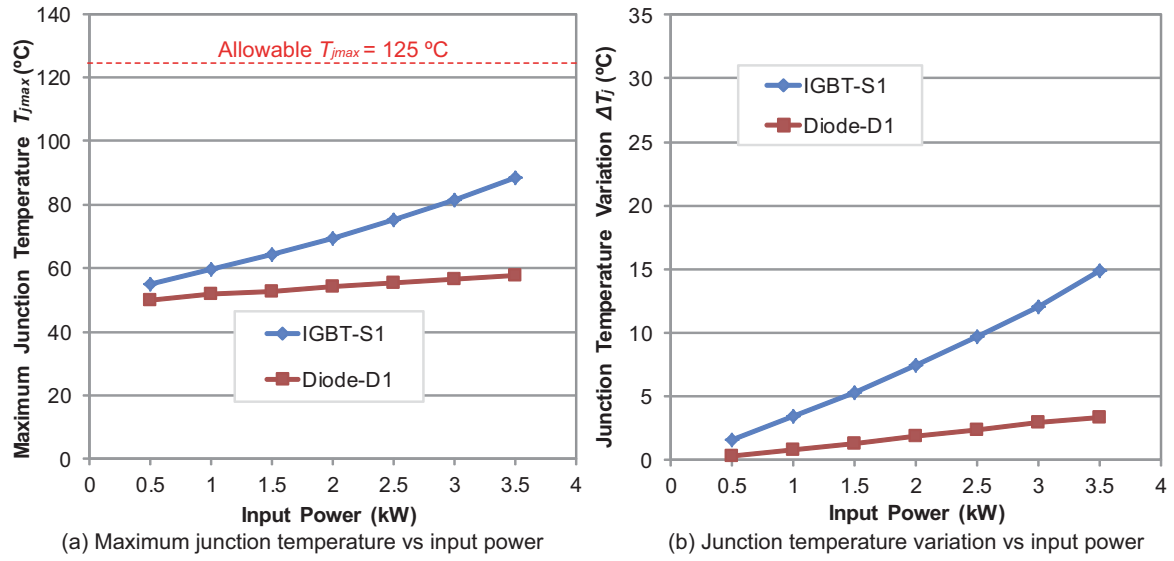
**Fig. 5.** Simulation results of a single-phase full-bridge PV inverter in different operation modes:  $v_g$ : grid voltage,  $i_g$ : grid current,  $P$ : active power,  $Q$ : reactive power,  $T_j$ : junction temperature, S: IGBT, D: diode, voltage sag depth: 0.45 p.u..



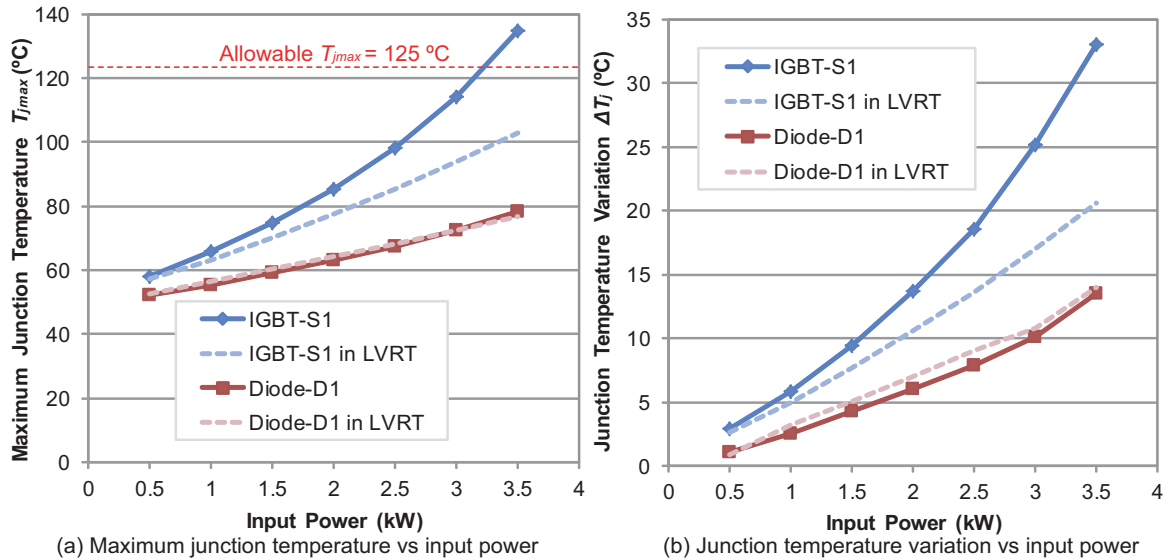
### 3.2 System Operation under Different Solar Irradiance Levels (Different Power Levels)

Taking the solar irradiance variation into account, the output power of PV panels and therefore the input power of the PV inverter are also varying in field operation. Thus, the system is examined under various power levels in different operation modes. The results are shown in Fig. 6 and Fig. 7.

As it is indicated in Fig. 6 and Fig. 7, under various solar irradiances, the power loading on the devices is different. Consequently, the maximum junction temperature and the junction temperature fluctuation will vary with the solar irradiances. This means that it is quite necessary to evaluate the thermal behavior of the power devices in consideration of the mission profiles. An extremely ambient condition will definitely impact the lifetime of the power device. For example, a suddenly changed solar irradiance may cause failures of the power modules.



**Fig. 6.** Junction temperatures of the power devices for a single-phase grid-connected full-bridge PV system in normal operation under different power levels (different solar irradiances).



**Fig. 7.** Junction temperatures of the power devices for a single-phase grid-connected full-bridge PV system under grid fault (0.45 p.u. voltage sag) with different power levels (different solar irradiances).

It is also shown in Fig. 7 that, by applying thermal optimized operation method to the system, the maximum junction temperature is controlled below the allowable value in LVRT condition. It demonstrates the effectiveness of the thermal optimized control method in the improvement of reliability under grid fault. Thus, it is better for the PV system to equip with low voltage ride-through capability in order to ensure the reliability of the entire system in different operation modes in the future.

## 4. Conclusions

In this paper, the thermal loading of IGBT modules in a single-phase full-bridge PV inverter is investigated under different operation modes and solar irradiance levels. A thermal optimized operation of the IGBT modules is achieved by injecting reactive current into the grid under LVRT mode. The amount of the reactive current depends on the depth of the voltage sag, which affects the junction temperature fluctuations. In the study of a 3 kW single-phase grid-connected PV inverter with the optimized operation, the maximum junction temperature and the junction temperature fluctuation of the IGBT modules are reduced by 30 °C and 15 °C respectively, under a voltage sag of 0.45 p.u.. Moreover, under different solar irradiance levels, the maximum junction temperatures are controlled below the allowable value specified in the datasheet with the help of thermal optimized operation. Therefore, the reliability of the IGBT modules and the entire PV inverters could be improved by means of the thermal optimized operation. In future work, the reliability improvement in terms of failure rate and lifetime will be quantified by taking into account typical mission profiles of solar irradiance. It is also concluded that it is better for the PV system to have low voltage ride through capability in order to achieve a high reliability in different operation modes.

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